Single wafer in-situ multiprocessing

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Abstract:
A description is given of the development of a novel single-wafer multiprocessin for flexible VLSI manufacturing that combines lamp heating, remote microwave processing, and photo processing in a single cold-wall chamber for multilayer i growth and deposition of dielectrics, semiconductors, and metals. Three examp multiprocessing technology are discussed: low-temperature growth of ultrathin dielectrics, selective and nonselective chemical vapor deposition of tungsten, an growth of silicon and silicon-germanium alloys.

Index Terms:
dielectric deposition semiconductor growth metal deposition selective CVD ther processing plasma etching single-wafer multiprocessing reactor VLSI manufact heating remote microwave plasma processing photo processing cold-wall cham multilayer in-situ growth low-temperature growth ultrathin dielectrics nonselec chemical vapor deposition epitaxial growth W deposition Si growth Si-Ge alloys vapour deposition elemental semiconductors heat treatment integrated circuit manufacture photolithography semiconductor growth silicon sputter etching va epitaxial growth VLSI

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SINGLE WAFER IN-SITU MULTIPROCESSING

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Abstract

Future success in microelectronics will demand rapid innovation, rapid product introduction and ability to react to a change quickly. These technological advancements in integrated electronics will require development of flexible fabrication technology for VLSI systems. In-situ multiprocessing equipment where several process steps can be done in sequence may be a key ingredient in this approach. For this environment to be flexible ability to change processing environment, extensive in-situ measurements and real time control will be the essential requirements. In this paper we will describe the development of a novel single wafer multiprocessing reactor next generation flexible VLSI manufacturing by combining lamp heating, remote microwave plasma and photo processing in a single cold-wall chamber and for multilayer in-situ growth and deposition of dielectrics, semiconductors and metals.

1 Introduction

For the past three decades, the semiconductor industry has made immense progress in increasing component densities and decreasing feature sizes. This progress in VLSI has been achieved through advances in equipment and fabrication technology, resulting in enormous economic benefits for commodity products, for which manufacturing of one kind of chip is done in large quantities.

As we look to the 1990's, it is clear that this mainstream approach has limitations with regard to the economic production of small quantities, fast turnaround time and learning, and research on innovative tools and processes:

- Processing is optimized by performing each step in the fabrication process on a separate piece of equipment, designed specifically for that step. With advances in technology, the number of steps to fabricate circuits is increasing. The resulting cost of setting up a factory to manufacture VLSI chips today is over 100 million dollars, which forces the manufacturer to produce a certain minimum number of chips to remain profitable.
- Efficiency is maximized by processing wafers in large batches. There are difficulties in efficiently tracking and scheduling wafers when the variety of part numbers is very large. This is an important issue in the production of logic for high end processors and where small quantities of a large variety of chips need to be fabricated using different technologies. It is also important for rapid prototyping of chips, in order to accelerate the learning cycle for innovative devices and processes.
- Variation is reduced by in-process and end-of-process monitoring. When there are several process parameters to optimize, statistical techniques require hundreds of wafers to be processed. Wafer batching inhibits the development and use of *in-situ* monitoring to accelerate the learning curve.
- The infrastructure of equipment vendors is focused on mass production. Research groups interested in developing innovative tools and processes are finding, therefore, that most commercial equipment is prohibitively expensive and lacks the desired flexibility. As a result we see mostly incremental development, rather than fundamental research in VLSI device physics and fabrication technology.

All of these factors point towards a need for new kinds of equipment and manufacturing techniques. We see a significant opportunity in a new class of equipment where *single wafers* are processed and *several fabrication steps* can be sequentially done in the *same equipment* by combining thermal, plasma, photo, and low pressure processing, in-situ monitoring, and extensive computer control. Implementation of this new class of equipment in a facility may be characterized by more economical small scale production, higher flexibility to accommodate many products on several processes, and faster turnaround and learning. It will also facilitate equipment and device innovation.

This new approach is particularly appropriate for the next generation of custom VLSI. Whereas the last generation was based on customized design in a standard technology (e.g., ASICs), its successor will benefit from customized processing technologies optimized for specific system applications. Hybrid technologies such as, BICMOS, GaAs on Si, and Ge/Si heterostructures, will be crucial.

The key technical ingredient in this approach is the combination of varied *in-situ* processes on a single, heavily instru-

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mented, flexible multiprocessing tool. The design of such a tool requires that it be limited to a single wafer.

For specific processes, such as lithography, ion implantation, and dry etching, single-wafer mode is the norm. By contrast, thermal processes (e.g., oxidation, chemical-vapor deposition, diffusion, and anneal) still employ batch furnaces. In recent years, rapid thermal processing (RTP) has been emerging as a viable technique for a wide range of applications in advanced VLSI technology. Originally introduced for the evaluation of ion-implantation processes, it has proved of value for many other applications, such as annealing, growth of thin gate dielectrics, silicide formation, CVD of tungsten, glass reflow, etc. In these applications, the merit of RTP lies in its ability to set precise temperatures and times in order to exploit differences in rate between desired and undesired processes.

Research on future VLSI processing is emphasizing lower temperatures and short times. These needs may be met by a natural extension to RTP, based on the use of plasma in conjunction with single-wafer lamp heating. It is not surprising, therefore, that there is a general agreement among experts that single-wafer multiprocessing technology will dominate the future generation of RTP for flexible microfabrication environments (e.g., low-cost microfactories).

We have developed a novel cold-wall single-wafer lamp-heated reactor employing rapid thermal, microwave remote plasma and photonic multiprocessing. We are developing techniques to use this reactor for multilayer *in-situ* growth and deposition of dielectrics, semiconductors, and metals. This equipment is intended to enhance semiconductor processing equipment versatility, improve process reproducibility and uniformity, increase growth and deposition rates at reduced processing temperatures, and achieve *in-situ* multiprocessing in conjunction with real-time process monitoring and automation.

2 Multiprocessing Technology Examples

The concepts of multiprocessing technology have already been demonstrated at Stanford through our preliminary work funded by DARPA. Technical feasibility of the multiprocessing technique has evolved through several years of research on rapid thermal processing and remote plasma low-temperature growth of ultrathin dielectrics [1]-[8], selective and non selective CVD of tungsten [9]-[11], and epitaxial growth of silicon and Si/Ge alloys [12]-[14].

Possible candidates for reliable ultrathin gate dielectrics in the sub-100 Å range for submicron MOS technology include oxides and nitroxides. Conventional furnace growth of these dielectrics offers a limited process window, because of slow temperature and gas flow transients. Since furnaces are designed for multiwafer batch processing, extensive *in-situ* real-time measurements are difficult to perform. Rapid thermal processing (RTP) provides very short process times at high temperatures and rapid change of the gaseous environment leading to the possibility of multicycle processing in a single chamber. Recent work has demonstrated excellent device characteristics in insulated gate field effect transistors (IGFETs) with gate insulators (50-60 Å) formed by in-situ RTP multiprocessing in O_2 and NH_3 ambients [2,6]. In particular, increased hot electron immunity and resistance against high energy electron irradiation has been observed. The flexibility of RTP was demonstrated by incorporation of RTP in several growth and annealing steps of NMOS process sequence by multicycle processing where process parameters were optimized for each cycle independent of others. All thermal steps except the field oxidation, polysilicon deposition, LPCVD of O_2 and metal deposition were done by RTP.

Among other growth and deposition processes, LPCVD of tungsten has emerged as a viable technology for VLSI applications such as low resistivity contacts and contact barriers, multilevel interconnections, and reduction of source/drain parasitic resistance, and in particular MOS gate electrodes. For submicron MOS devices W-gate technology offers not only low resistivity but more importantly ideal work function for NMOS and PMOS devices. W-gate technology has not become very popular because the conventional hot-wall LPCVD furnaces are not appropriate for nonselective formation of tungsten on insulators unless a glue layer like Si or another metal is used, however, that approach does not yield the ideal device characteristics [11]. In our recent work we have demonstrated that by using remote microwave plasma technology non selective deposition of tungsten can be done without the use of a glue layer and without any damage to the MOS device generally encountered in rf plasma technology or sputtering [9]. We have also demonstrated the feasibility of low-temperature nitridation of silicon in nitrogen plasma generated by remote microwave discharge [5].

In a related work at Stanford on *Limited Reaction Processing* lamps have been used as a thermal switch to grow extremely abrupt layers of epitaxial Si and Si/Ge alloys [12]-[14]. These hetrostructures open totally new domains of novel devices.

In summary, our research in the area of single-wafer thermal processing [5]-[7] suggests that rapid thermal/plasma/photo multiprocessing has significant potential for *in-situ* fabrication of future high-performance semiconductor devices.

The combination of single-wafer rapid thermal processing, microwave remote plasma processing, and photo processing should provide a powerful multipurpose reactor for semiconductor device fabrication. Additionally, *in-situ* multiprocessing should reduce contamination, enhance circuit yield, and allow the formation of new improved device structures. The next section describes an attempt in this direction.

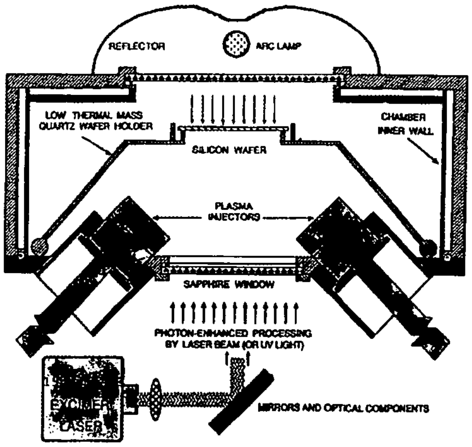

Figure 1: Schematic of the cold-wall single-wafer rapid thermal/microwave plasma/photo multiprocessing reactor.

3 Multiprocessing Reactor

Figure 1 shows a schematic of the simplified prototype design employed to obtain the preliminary results. The overall system is very flexible for *in-situ* multiprocessing because it allows rapid cycling of ambient gases, temperature, plasma, and photo source. It allows several processing steps to be done sequentially *in-situ*, while providing sufficient flexibility to allow optimization of each processing step.

A water-cooled stainless steel chamber provides ports for gas injection, optical heating of the wafer, vacuum pumping, and *in-situ* process monitoring. The wafer sits on low thermal mass quartz pins facing the end cone of a discharge tube and is heated on the other side by a lamp. The optical flux reaches the wafer through a water-cooled quartz window. The wafer temperature can be controlled in a range from room temperature to 1150°C for seconds up to many minutes. The gas distribution network permits a large variety of gases (Ar, Ne, N_2, O_2, NH_3, NF_3, forming gas, N_2O, HCl, SF_6, WF_6, heated WCl_6 solid source, H_2, SiH_4, GeH_4, and SiF_4) to be injected into the chamber either singly or in safe combinations. Injection is either through a plasma injectors at the bottom of the chamber or through side port nonplasma injectors.

Remote plasma is generated inside the tube by a microwave discharge cavity operating at 2450 MHz. The remote microwave plasma approach differs from conventional localized plasma techniques. It allows selective and controlled generation of specific plasma species simultaneous with injection of additional nonplasma gases into the process chamber, without the complications of gas discharge in a composite gas ambient. In addition to allowing low temperature dielectric growth and LPCVD of insulators and silicon epitaxy, remote plasma processing has enabled us to develop several new processes for nonselective deposition of tungsten and its compounds (e.g., nitrides) on insulating layers for MOS gate applications.

A sapphire window at the bottom allows photon-enhanced processing by incoherent UV source or scanning excimer laser beam. This sapphire window can also be employed for *in-situ* process monitoring such as temperature measurement. The availability of plasma and photon-enhanced processing makes optimization of various processes possible. This configuration can also be employed for a direct comparison of microwave discharge and optical excitation in enhancing the growth/deposition rates or promoting new processes.

Automated semiconductor manufacturing should meet the requirements such as enhanced fabrication yield and throughput. Single-wafer rapid thermal/plasma processing can be an important part of computer integrated manufacturing. In contrast to batch thermal processing, the wafer-to-wafer process uniformity in single-wafer processing is a run-to-run uniformity issue. As a result, the task of equipment modeling and characterization of the correlations among equipment and process parameters will be less complicated and more time-invariant. The computer database will provide a variety of process recipes for wafer processing. The important real-time process parameters (temperature distribution, gas flow pattern, pressure, plasma intensity, electron and ion energies and densities, optical intensity of the source lamps, thickness and resistivity data, ...) will be monitored in real time by the computer. These data can be employed to perform additional real-time adaptive process control, yield studies, and statistical process analysis. We believe that this multipurpose reactor will serve as an ideal advanced equipment for research on computer integrated flexible manufacturing.

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